Co-Design of Power Amplifier and Narrowband Filter using High-Q Evanescent-Mode Cavity Resonator as the Output Matching Network

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***Abstract*— A unique GaN power amplifier (PA) with an integrated evanescent-mode resonator as its output matching network is presented in this paper. Instead of matching the output of the GaN transistor to 50 Ω and connecting it to a 50-Ω bandpass filter, the GaN is directly integrated with a one-pole filter thus eliminating the conventionally-employed output matching network after the GaN transistor. This leads to a reduced circuit complexity and higher efficiency. The one-pole filter implemented by a strongly-coupled evanescent-mode cavity resonator with an unloaded quality factor of 320 is experimentally presented as a proof-of-concept demonstration. This design yields a very narrowband PA response from $1.24-1.275$ GHz (2.8%), which is comparable to the bandwidth of typical communication signals. The PA exhibits a state-of-the-art performance of $> 70\%$ efficiency, > 10 dB gain, > 30 dBm output power, and second and third harmonic levels of < -70 dBc. The presented methodology has the potential to be further extended to a tunable design for multi-band applications.**

***Index Terms*— Power amplifier, evanescent-mode cavity, narrowband filter, high efficiency.**

I. Introduction

In modern wireless communication systems highly efficient but highly non-linear power amplifiers (PAs) are typically followed by bandpass filters that eliminate the adjacent channel power leakage (ACPL) and harmonics [1] as illustrated in Fig. 1(a). In conventional topologies (Fig. 1(b)), the PA and filter are independently designed based on a 50 Ω system impedance. Nevertheless, the input impedance of the filter may be designed to directly match the transistor output, which usually needs a non-50 Ω impedance, as shown in Fig. 1(c). As a result, the PA output matching network is replaced by the filter, leading to a decrease of the circuit complexity and an enhancement of the overall efficiency.

Recently, high-Q evanescent-mode resonators have been demonstrated in designing narrowband filters [2]–[4], achieving very narrow bandwidths ($0.5\% - 2\%$), low insertion losses ($\cong$ 3 dB) and very large spurious-free regions. These techniques yield a good potential to realize the filter shown in Fig. 1(a). Moreover, the evanescent-mode cavity can be directly integrated in the same substrate as the PA, which makes co-designing the PA and filter particularly practical. It is also worth noting that tuning methods such as those presented in [2]–[4] may be employed in this technique to create reconfigurable PA-filter modules for multi-band applications.

To demonstrate the co-design technique, an evanescent-mode cavity resonator (a one-pole filter) is designed as the

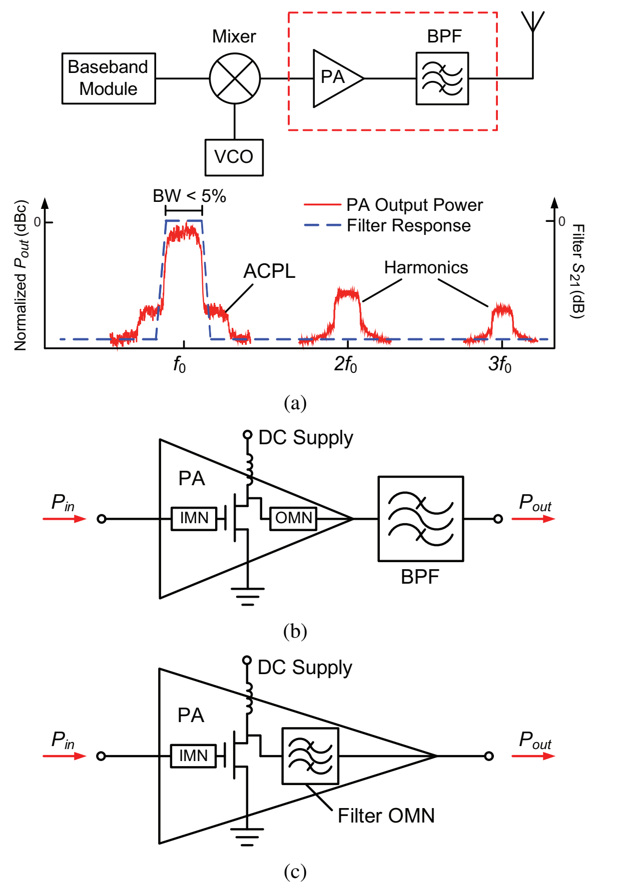


Fig. 1. (a) PA and filter cascade in an RF transmitter. (b) Conventional independent design of the PA with its input matching network (IMN) and output matching network (OMN) and bandpass filter. (c) Co-design of PA and filter.

output matching network of a commercially-available GaN transistor. The entire PA-filter circuit is integrated in a single Rogers TMM-3 substrate. The measured 3-dB bandwidth of this PA-filter module is about 35 MHz centered at 1.257 GHz (2.8%). A measured PA efficiency of higher than 70% and a gain of $>$ 10 dB (output power level $>$ 30 dBm) are achieved within the passband. The measured PA performance is comparable to the conventional single-band PA designs [5]–[7], which typically have a $> 70\%$ efficiency and > 10 dB gain.

II. Co-Design of Power Amplifier and Filter

A. PA-Filter Topology Based on Evanescent-Mode Cavity Resonator

A Cree GaN HEMT transistor (CGH40025) is utilized to implement the power amplifier. The output matching network of a typical highly efficient PA should provide the optimal impedance at the PA's fundamental frequency and specific impedances at its harmonic frequencies (e.g., infinite harmonic impedances for Class-E PA mode) [8]. In this design, these two requirements will be achieved by a strongly-coupled evanescent-mode cavity resonator.

The optimal output impedance (Z_{OPT}) (L-band) of this Cree transistor at $1-2$ GHz is found from the load-pull simulation using Agilent's Advance Design System ADS [9]. Fig. 2 illustrates how Z_{OPT} is matched by the cavity-resonator-based output matching network. For an ideal strongly-coupled evanescent-mode cavity resonator the input impedance (Z_{Res}) moves along the constant-conductance circle on the Smith chart when the frequency varies. This is denoted by the red trajectory in Fig. 2. This impedance becomes Z_0 at the resonant frequency f_0, which is within the $1-2$ GHz band in this design. At a frequency slightly higher than f_0 (this will be the design frequency for the PA, f_{PA}), Z_{Res} has the same real part as the optimal impedance Z_{OPT}. Consequently, using a series inductor, the input impedance of the resonator can be brought to Z_{OPT} at the frequency f_{PA}. Outside of the passband the resonator provides ideally a reflection coefficient of $|\Gamma| = 1$, so the harmonic powers will be prevented from being generated. Thus, a high PA efficiency can be achieved.

A 3D schematic of this PA-filter is shown in Fig. 3(a). The circuit model of this PA-filter module is shown in Fig. 3(b). The equivalent circuit of the coupled evanescent-mode cavity resonator is depicted inside the red dotted rectangle. It is modeled as an LC resonator with the external coupling structures. The series inductor in Fig. 2 is implemented with a transmission line section (TL1), which also acts as the feed-

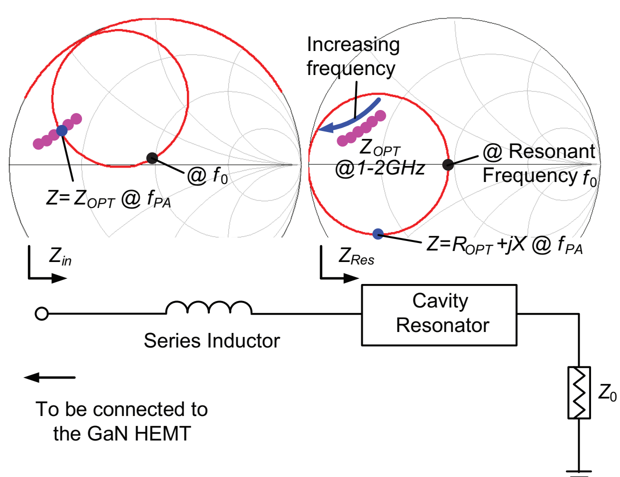


Fig. 2. Matching scheme for the Cree GaN transistor with evanescent-mode cavity resonator.

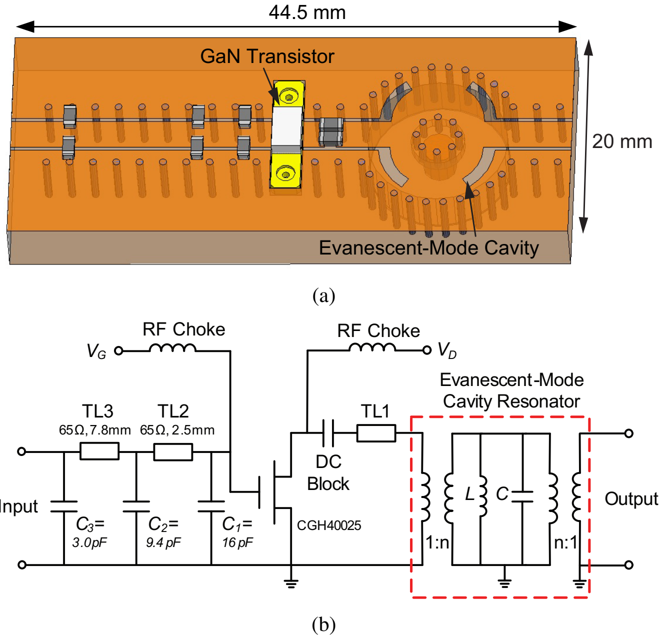
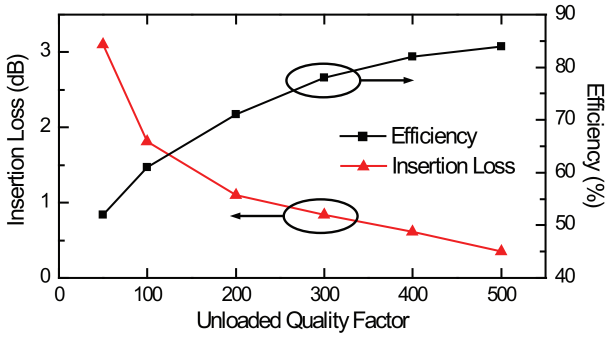


Fig. 3. Power amplifier based on evanescent-mode cavity resonator: (a) 3D schematic of the substrate-integrated circuit, (b) circuit model.

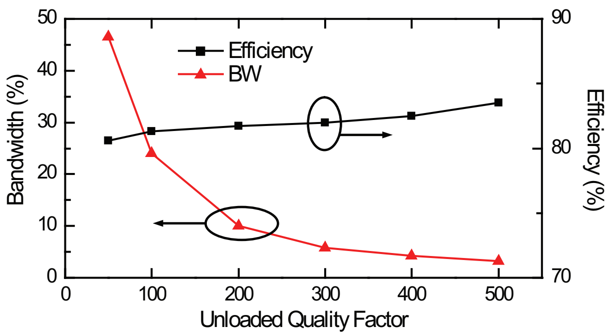
line of the cavity. The transistor input is matched to Z_0 within the $1-2$ GHz bandwidth using a multi-stage ladder network. The parameters of each element in the input matching network are presented in Fig. 3(b).

B. Impact of the Resonator Quality Factor

In this PA-filter design, the unloaded quality factor (Q_u) of the resonator plays a key role in determining the performance of the entire module. In order to investigate the effect of the unloaded quality factor, the circuit model shown in Fig. 3 is simulated with a variable Q_u-factor of the resonator. The parameters used in this investigation are: $L = 1.5$ nH, $C = 11.2$ pF, $f_0 = 1.22$ GHz (derived using the model presented in [2]). Two families of simulations are performed. In the first case (constant bandwidth $-$ Fig. 4a) the 3-dB bandwidth of the resonator is kept constant at 3.2% by maintaining the external coupling coefficient at a value of $n = 3$. In this case when Q_u drops from $500-50$, the insertion loss is increased from $0.3-1.5$ dB and the PA efficiency is degraded significantly from $83\%-58\%$. In the second case (constant insertion loss $-$ Fig. 4(b)), the insertion loss of the resonator is maintained constant at 0.3 dB for different Q_u by adjusting the coupling coefficient. These simulations indicate that a higher Q_u leads to a narrower bandwidth. It also underlines that a high PA efficiency (e.g. 80%) may be achieved even with a low Q_u as is commonly the case with planar PCB-based circuits [5]. However, the simultaneous requirements of both narrow bandwidth ($< 5\%$) and high PA efficiency ($> 70\%$) require $Q_u > 300$.



(a)



(b)

Fig. 4. Impact of quality factor on (a) insertion loss (constant bandwidth), (b) bandwidth (constant insertion loss).

TABLE I
FINAL CAVITY MODEL PARAMETERS USED IN SIMULATIONS

Post area	$\pi \times 1.4^2$ mm^2
Initial RF gap g_{RF}	37 μm
Cavity depth	4 mm
Cavity area	$\pi \times 6^2$ mm^2
Simulated Q_u at f_0	320

C. Final Design of the Cavity-Resonator-Based Output Matching Network

To implement this PA-filter module, an evanescent-mode cavity resonator with $f_0 = 1.22$ GHz is designed using Ansoft's HFSS [10]. In the cavity resonator design, there is always a trade-off between Q_u and the cavity dimensions, including the post size and the gap distance between the post top and cavity ceiling [2]. The finalized parameters of this cavity filter are listed in Table I. To match the output impedance of the GaN transistor, the designed feed transmission-line (TL1 in Fig. 3) has an impedance of Z_0 and a length of 6.8 mm. Fig. 5 shows the HFSS-simulated frequency response and the input impedance of the designed output matching network. The center frequency of the resonator is 1.22 GHz and the actual PA operation frequency is 1.25 GHz, as shown in Fig. 5. It is also observed that this cavity-resonator-based output matching network (OMN) yields an excellent performance at harmonic frequencies ($S_{11} \cong 0$ and $S_{21} < -30$ dB for $f < 4f_0$), leading to a good restriction of the harmonic power generations.

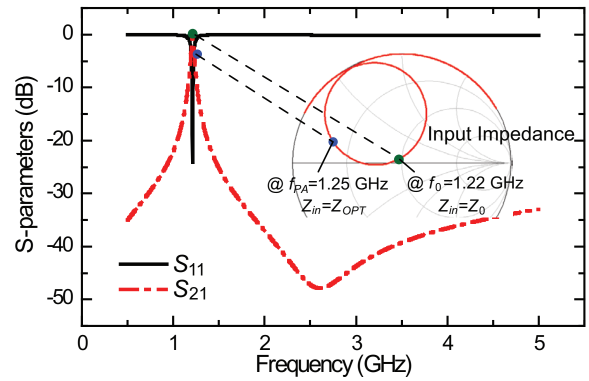
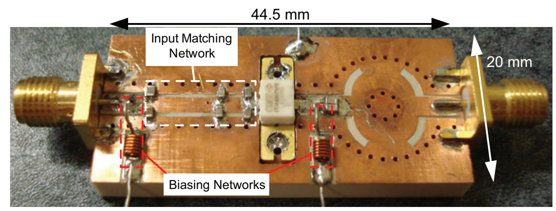
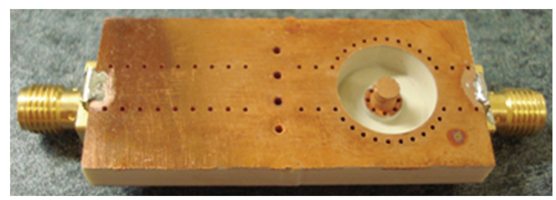


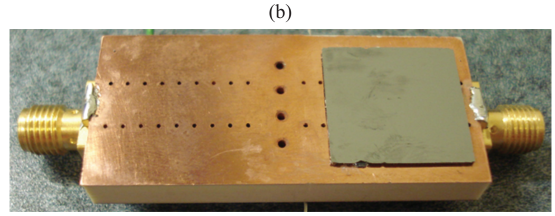
Fig. 5. Modeled frequency response of the cavity-resonator-based output matching network.



(a)



(b)



(c)

Fig. 6. Fabricated circuit: (a) front-side, (b) back-side with unsealed cavity, (c) back-side with sealed cavity.

III. MEASUREMENTS AND DISCUSSION

The entire PA-filter circuit is machined in a Rogers TMM substrate (TMM3) with a thickness of 5.08 mm. The fabrication of the cavity resonator follows the same procedure presented in [2]. Fig. 6 shows the fabricated circuit. The input matching network, feed lines and coupling structures are defined on the front-side where the GaN transistor is mounted, as shown in Fig. 6(a). As the cavity feed lines are shorted to ground, two parallel 51-pF capacitors are mounted at the output of the transistor as DC blocks. The biasing networks at the drain and gate are implemented using DC feed wires and Coilcraft aircoil inductors (27 nH). The evanescent-mode cavity is machined on the back-side of the substrate (Fig. 6(b)). A gold-plated silicon piece with a thickness of 0.5 mm is attached to the cavity using silver-epoxy, as shown in Fig. 6(c).

The power amplifier is tested under the stimulus of a

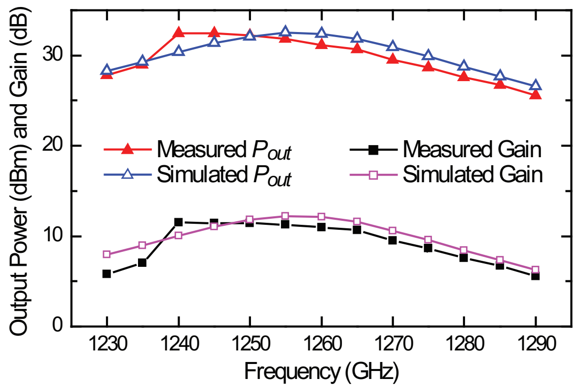


Fig. 7. Measured and simulated PA output power and gain under CW stimulus.

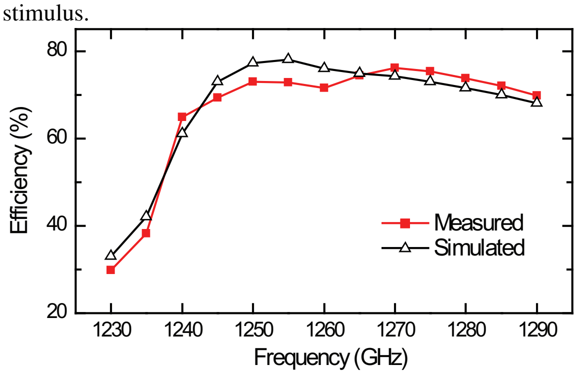


Fig. 8. Measured and simulated PA drain efficiencies.

continuous wave (CW) signal. The gate of the transistor is biased at the threshold of 3 V. The drain bias of the transistor is 6.5 V. Fig. 7 shows the measured PA output power and gain from $1.23-1.29$ GHz. Good agreement between measurements and simulation is observed. The maximum output power of 32.6 dBm and maximum gain of 11.8 dB occur at 1.24 GHz. Fig. 8 shows the measured and simulated PA efficiencies. The measured PA efficiency is $> 70\%$ above 1.245 GHz and has a maximum value of 76.8% at 1.27 GHz. The efficiency achieved by this PA-filter module is comparable to the state-of-the-art high-efficiency single-band PAs [5]–[7], which are traditional planar circuits and have bandwidths of $> 30\%$. These implementations, however, do not include the loss due to the filter that would normally follow them. Fig. 9 plots the measured second and third harmonic levels when the PA is operating from 1.23-1.29 GHz. The measured harmonic powers are very low (< 70 dBc), which is mainly due to the good filter behavior of the evanescent-mode cavity resonator.

IV. Conclusion

This paper presented, for the first time, a methodology for co-designing PA and an evanescent-mode filter as its output matching network. Instead of designing PA and filter independently based on a 50-Ω system-impedance and connecting them in cascade, the transistor is directly integrated with the filter. Thus, the output matching network is eliminated, leading to a reduced circuit complexity and higher overall efficiency. To demonstrate this technique experimentally, a

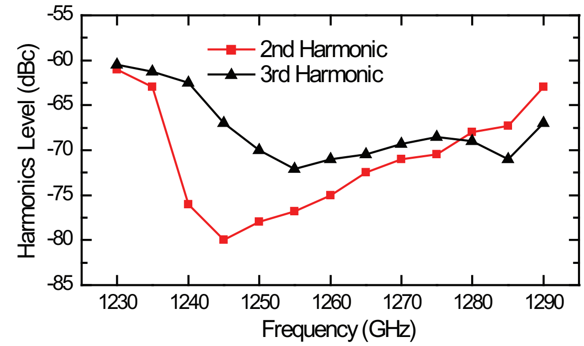


Fig. 9. Measured harmonics level of the power amplifier.

GaN PA is co-designed with a one-pole filter implemented by a strongly-coupled evanescent-mode cavity resonator with a Q_u of 320. This design yields a very narrowband PA response from $1.24-1.275$ GHz (2.8%, comparable to the bandwidths of typical communication signals). A state-of-the-art PA performance is also achieved, i.e. a $> 70\%$ efficiency, > 10 dB gain, > 30 dBm output power, and < -70 dBc harmonics level. This methodology can be further extended to a tunable design for multi-band applications.

Acknowledgement

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